Axiom Propeller tests in the Emerson Cavitation Tunnel

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ABSTRACT
The Emerson Cavitation Tunnel at Newcastle University recently conducted a series of open water model tests on a unique 3 bladed propeller, commercially known as “Axiom Propeller”, intended for the narrow-boat and sailboat market. The purpose of the tests was to measure the performance and cavitation characteristics of this propeller with a bi-directional thrust capability making use of its skew symmetric blade sections, and to compare its performance to an earlier variant of the design, also tested in the Emerson Cavitation Tunnel by Seo et al (2010). The study of the propeller included open water and stopping conditions (1st & 2nd quadrant) as well as the effect of cavitation over a range of achievable advance coefficients. This paper presents the design background, a description of the test set-up; the results of the multi-quadrant performance tests at atmospheric condition together with a short review of the cavitation observations for this unusual propeller.

Keywords
Skew symmetric blade section, open water performance, cavitation, experimental study.

1 INTRODUCTION
The Axiom propeller is a unique 3 bladed propeller that is designed for the low speed / lightly loaded, narrow boat and sailboat market. The design differs from the more conventional propeller geometry of aerofoil type propeller sections in-so-far as it has an unusual ‘s’ type skew-symmetric blade section with spade like blades outlines shown in Figure 1. This symmetry allows the propeller to generate the same amount of thrust going ahead as it does going astern, one of its key design features, enabling it to be a bi-directional thrust propeller.

Figure 1. The Axiom propeller showing the unusual ‘s’ type section on a 3 blade propeller

Figure 2 shows an Axiom propeller design fitted to a narrow boat. The unique propeller performs well in low speed, sailing in restricted waters, all often at typical Froude numbers of Fn = 0.12 or lower. Advocates for the Axiom design claim improved handling, greater fuel efficiency, reduced ‘prop-walk’ and impressive stopping performance for their vessels. This is important as the vessel operates at very low speed in restricted canal waterways where manoeuvrability and stopping ability are the key performance requirements rather than attainable speed.

The design for the Axiom propeller was developed somewhat heuristically and the parent design suffered from a low open water efficiency of around 35 %. This was encouraging given that no experimental testing or validation in a research facility had been performed adopting a trial and error style of optimisation; all of which encouraged the designers to pursue further optimisation. For the early Axiom design, trials were conducted in a simple manner as reported by Langley (2009). For these trials two 14.93 m (49 ft) narrow boats of identical design and powering were used; the first fitted with a conventional propeller, the second with the Axiom propeller. The boats were run along the same stretch of canal approximately 100 m apart. The trials were conducted by running the boats at the same shaft rotational rate (rpm) and timed between various destinations. The canals were typically shallow, with bank and depth effects; the conditions of the hulls were not specified. A series of return runs were also performed in an effort to reduce the effects of current on the
results. However despite this rudimentary trials procedure, the tests showed the benefit of the Axiom design. When compared to the conventional design the Axiom propeller showed an increase in speed and handling for the same rpm but with a drop in vibration. Figure 3 shows the boats during the trial at the same rpm.

Figure 3. Performance trials with the regular propeller (top) and the Axiom propeller (bottom) at the same rpm

The trials team noted the different wave patterns and wake created by the various designs, visible in Figure 3, but failed to recognise that the wave patterns were speed dependent and would change from favourable to unfavourable depending upon Froude number, and several other factors. The trials team also observed that the differing wave characteristics caused the vessel to be drawn towards the canal wall more for the larger wave system requiring more use of the tiller to maintain heading. This was clearly a speed, and hence wave characteristic, and something that would have been eliminated from the comparison if the forward speed were to have been matched rather than the rpm. Finally, the two test propellers were also very different in their stopping ability. The conventional propeller stopped the boat from walking pace in 1 ship length; with the Axiom it was half of that.

Whilst the design is appealing for it’s manoeuvring characteristics, its cavitation and loading potential were unknown beyond these simplistic trials. To fully understand the capabilities and the limitations of the blade design a series of scientific trials and investigations were required. In collaboration with the Emerson Cavitation Tunnel, Axiom Propellers optimised their blade design to reduce the spade like blade outline shown in Figure 4 to a more conventional Kaplan geometry shown in Figure 5. It was hoped that the new design could be more efficient and operate at higher speeds whilst still utilising the bi-directional thrust capability to the full. To understand the limitations of this new design, a further series of model tests were performed to assess the improvements in performance due to these design changes.

Figure 4. The original Axiom propeller design

Figure 5. The optimised Axiom propeller design

Following this introduction in Section 1, Section 2 gives the test set-up and Section 3 gives the results of the open water performance tests including the first two quadrant data for this propeller. Section 4 gives a short review of the cavitation observations in the 1st and 2nd quadrant and Section 5 draws conclusions from the results.

2 IMPLEMENTATION OF EXPERIMENT

The propeller tests were conducted in the Emerson Cavitation Tunnel (ECT) in May 2012 as reported by Sampson et al (2012). The ECT is a closed circuit depressurised tunnel located within the University of Newcastle. A schematic of the tunnel circuit is given in Figure 6. The ECT has a measuring section of 3.2m x 1.2m x 0.8m; a contraction ratio of 4.274:1 and is therefore considered a medium sized facility. During recent years, numerous improvements to the instrumentation equipment and measuring section have taken place all increasing the capabilities of the facility. In 2008, the tunnel was upgraded with the installation of a new measuring section,
guide vanes, honeycomb, quick degassing system and automated control system. The basic specifications for the tunnel are given in Table 1 whilst the details of this recent upgrading was reported in Atlar (2011).

Table 1. Emerson Cavitation Tunnel specification

<table>
<thead>
<tr>
<th>Facility type</th>
<th>Emerson Cavitation Tunnel</th>
</tr>
</thead>
<tbody>
<tr>
<td>Test section (LxBxH)</td>
<td>3.10m x 1.22m x 0.81m</td>
</tr>
<tr>
<td>Contraction ratio</td>
<td>4.271</td>
</tr>
<tr>
<td>Drive system</td>
<td>4 Bladed axial flow impeller</td>
</tr>
<tr>
<td>Main pump power</td>
<td>300 kW</td>
</tr>
<tr>
<td>Impeller diameter</td>
<td>1.4 m</td>
</tr>
<tr>
<td>Maximum velocity</td>
<td>8 m/s (15.5 knots)</td>
</tr>
<tr>
<td>Abs. pressure range</td>
<td>7.6 kN/m2 to 106 kN/m2</td>
</tr>
<tr>
<td>Cavitation number</td>
<td>0.5 (min) to 23 (max)</td>
</tr>
</tbody>
</table>

Table 2. Propeller Axiom I Characteristics

<table>
<thead>
<tr>
<th>Scale</th>
<th>1:1</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of blades</td>
<td>3</td>
</tr>
<tr>
<td>Diameter</td>
<td>0.3m</td>
</tr>
<tr>
<td>Pitch / diameter ratio at r/R = 0.7</td>
<td>0.847</td>
</tr>
<tr>
<td>Blade area ratio</td>
<td>0.7</td>
</tr>
<tr>
<td>Direction of rotation</td>
<td>Right</td>
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</table>

Table 3. Propeller Axiom II Characteristics

<table>
<thead>
<tr>
<th>Scale</th>
<th>1:1</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of blades</td>
<td>3</td>
</tr>
<tr>
<td>Diameter</td>
<td>0.3m</td>
</tr>
<tr>
<td>Pitch / diameter ratio at r/R = 0.7</td>
<td>1.0</td>
</tr>
<tr>
<td>Blade area ratio</td>
<td>0.5</td>
</tr>
<tr>
<td>Direction of rotation</td>
<td>Right</td>
</tr>
</tbody>
</table>

The model propeller was manufactured by Axiom Propellers in Bronze to fit a 1 ¼” dynamometer shaft. The propeller was 300 mm diameter with a pitch to diameter ratio (P/D) of 1.0 and a blade area ratio (BAR) of 0.5. Table 3 gives the main particulars of the propeller whilst Figure 7 shows the propeller prior to the test.

In order to assess the efficiency performance of the propeller, open water tests at atmospheric condition were conducted. The tests were performed to cover a practical range of advance coefficient ($J$) varying between $J = 0.30$ and $J = 0.75$ under normal atmospheric conditions. For the tests the tunnel water speeds were held at 3.0 m/s and 4.0 m/s, whilst the rotational rate of the propeller was varied to cover the above range of J values. Finally the data was non-dimensionalised using standard ITTC (2002) test procedures. The equations used in the analysis for the advance coefficient ($J$), thrust coefficient ($K_T$), torque coefficient, ($K_Q$), and open water efficiency ($\eta_o$), are given in Equations 1 ~ 4:

$$J = \frac{\nu}{nD}$$  \hspace{1cm} (1)

$$K_T = \frac{T}{\rho n^2 D^3}$$  \hspace{1cm} (2)

$$K_Q = \frac{Q}{\rho n^2 D^3}$$  \hspace{1cm} (3)

$$\eta_o = \frac{K_T}{K_Q} \times \frac{J}{2\pi}$$  \hspace{1cm} (4)
Reynolds number

\[ R_e = \frac{A_e}{A_0} \times \frac{nD^2}{\nu} \]  

(5)

Cavitation number

\[ \sigma_c = \frac{p-e}{\frac{1}{2} \rho (V_i)^2} \]  

(6)

Where, \( V \) is the tunnel free stream water velocity (m/s), \( n \) is the rotational speed of the propeller (rpm), \( T \) is thrust of the propeller (N), \( Q \) is the torque (Nm) of the propeller, \( D \) is the propeller diameter (m) \( A_e \) is the expanded area (m²), \( A_0 \) is the disk area (m²), \( p \) is the absolute pressure at the propeller disk (Pa); \( e \) is the vapourisation pressure (Pa), \( \nu \) is the kinematic viscosity (cm²/s) and \( \rho \) is the density of the tunnel solution (kg/m³).

In addition to the open water tests, which represent the first quadrant performance of the propeller, i.e. the propeller working with positive rotational speed and positive advance velocity, the additional 3 quadrants were required. The 4 quadrant data therefore represents any flow condition experienced by a propeller during manœuvreuring. During these tests the propeller may be rotated in the ahead (clockwise) or astern (anti-clockwise) directions while the direction of the tunnel flow was kept in the same (ahead) direction. The physical orientation of the propeller could have been changed back to front to simulate the appropriate quadrant according to the notation described below. However given the symmetrical nature of the design, only the first two quadrants were actually required the latter two (3rd & 4th quadrant) being generated from the former owing to the skew symmetric nature of the data.

In the case of a fixed pitch propeller it is conventional to define the four quadrants based on an advance angle (\( \beta \)) defined in Equation 7. Using this nomenclature the 4 quadrants can be easily identified and are given in Table 4.

Advance angle

\[ \beta = \tan^{-1} \left( \frac{V_o}{0.7 \pi nD} \right) \]  

(7)

Table 4: The 4 quadrant propeller performance data

<table>
<thead>
<tr>
<th>Quadrant</th>
<th>Description</th>
<th>Advance speed</th>
<th>Rotational speed</th>
<th>Adv. angle</th>
</tr>
</thead>
<tbody>
<tr>
<td>2nd</td>
<td>(Stopping in ahead)</td>
<td>– ahead</td>
<td>– astern</td>
<td>90 &lt; ( \beta ) ≤ 180</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1st</td>
<td>Going ahead</td>
<td>– ahead</td>
<td>– ahead</td>
<td>0 ≤ ( \beta ) ≤ 90</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3rd</td>
<td>Reversing</td>
<td>– astern</td>
<td>– astern</td>
<td>180 &lt; ( \beta ) ≤ 270</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>4th</td>
<td>Stopping in astern</td>
<td>– astern</td>
<td>– ahead</td>
<td>270 &lt; ( \beta ) ≤ 360</td>
</tr>
</tbody>
</table>

It should be noted that when \( \beta = 0^\circ \) or \( \beta = 360^\circ \) then this defines the ahead bollard pull condition and when \( \beta = 180^\circ \) this corresponds to the astern bollard pull situation. For \( \beta = 90^\circ \) and \( \beta = 270^\circ \), these positions relate to the condition when the propeller is not rotating and is being dragged ahead or astern through the water respectively. The thrust coefficient (\( C_T \)) and torque coefficient (\( C_Q \)) for this analysis are defined using the resultant velocity and are given in Equations 8 and 9.

Thrust coefficient

\[ C_T = \frac{T}{\frac{\pi}{8} \rho \left( V_o^2 + (0.7 \pi nD)^2 \right) D^2} \]  

(8)

Torque coefficient

\[ C_Q = \frac{T}{\frac{\pi}{8} \rho \left( V_o^2 + (0.7 \pi nD)^2 \right) D^2} \]  

(9)

3 RESULTS AND DISCUSSION

The Axiom (Mark II) propeller showed a marked improvement in terms of performance, cavitation and noise over the previous design (Mark I). To understand this increase the open water performance, 4 quadrant data and the cavitation patterns were analysed and compared to the original propeller.

3.1 Open water analysis

A plot of the open water performance of the Axiom Mark II propeller is given in Figure 8. The data is given for thrust (\( K_T \)), torque (10\( K_Q \)) and efficiency (\( \eta_p \)) for all of the experimental points gathered. The data has been subsequently processed using least squares fit to give the backbone curves for each of these variables.

![Figure 8. Open water plot for Axiom Mark II propeller](image)

The Mark II Axiom propeller provided very repeatable test data with only small test-to-test variation. The maximum efficiency was 53.7% at \( J = 0.575 \). When this was compared to the Mark I propeller it is clear that the reduction in blade area and tapered blade outline as opposed to the plan form (square shape) between the two designs has had a significant positive effect on the efficiency. A comparison of the open water plots is given in Figure 9, it
is clear that the new design was approximately 63% more efficient. The new propeller also has a wider range of achievable advance coefficients due to the increase in pitch ratio from P/D = 0.86 to P/D = 1.0 changing the operating point for the propeller from J = 0.35 (cavitating) to J = 0.575 (non-cavitating). This helped the Mark II propeller operate in a virtually cavitation free condition at the design point.

3.2 Multi-quadrant tests

The Multi-quadrant tests were conducted by appropriately varying the tunnel flow speed (V), propeller shaft speed (n), direction of shaft speed (clockwise and anti-clockwise) and direction of tunnel flow (ahead and astern) via the relative position of the propeller with respect to flow as outlined in Section 2. Figure 10 shows the results of the Mark I Axiom propeller presented in the classical four quadrant notation of CT and 10CQ against β.

The Axiom propeller has symmetric characteristics in almost all quadrants, as well as the skew symmetry of CT and CQ curves; this is not the case for the conventional propellers, which are usually optimised for the forward motion only. Obviously this is a favourable attribute for the Axiom propeller for stopping and reversing as well as controlling the course keeping in both directions, ahead and astern, with almost similar performance. The small discontinuities around β = 0°, 90°, 180°, 270° and 360° are due to the physical limitations of the facility. These values can be obtained from the values around their vicinity by simple interpolation.

3.3 Cavitation observations

The cavitation patterns on the Mark II were similar to the first version of the propeller. The S type section is not ideally suited to heavily loaded conditions as it promotes significant levels cavitation mid chord on the blade. The
cavitation inception began at approximately \( J = 0.55 \). At \( J = 0.45 \) the tip vortex cavitation was a thin fully developed filament. At the leading edge between \( r/R = 0.7 \sim 0.9 \) a small area of sheet cavitation began to develop. This sheet cavity would transit the chord as the \( J \) value was reduced to eventually combine with the tip vortex cavitation. However in this condition it extended approximately 5% of the chord.

At \( J = 0.40 \) the cavitation types present on the blade began to stabilise. The sheet cavitation covered 10% of the blade mostly focused around \( r/R = 0.8 \). However at this condition the end of the sheet cavity was becoming unsteady and small wisps of erosive cloud cavitation could be detected. The tip vortex remained in position but increased in strength. By \( J = 0.35 \) the sheet cavitation covered half of the chord for each blade. The unsteady nature of the after part of the cavity was generating significant levels of mist cavitation, which would most certainly be erosive. The sheet cavity was also influencing the tip vortex cavitation, which too was starting to become unsteady and break down.

At \( J = 0.30 \), the sheet cavitation covers more than 90% of the blade at \( r/R = 0.8 \) and has begun to interact with the tip vortex cavitation. For this condition both the sheet and tip vortex cavitation are starting to break down and generate unsteady cavitation coupled with large amounts of erosive cloud cavitation.

Cavitation observations were made with the propeller in the 1st and 2nd quadrant runs at atmospheric condition. The results are given in Figure 13 for a range of \( J \) values (\( J = 0.30 \sim J = 0.45 \)). For the tests, the tunnel was open to atmosphere; the flow velocity was kept constant (\( \sigma_v = 23 \)), whilst the shaft rpm was varied to cover the range of operational conditions.

Figure 13. Open water images (\( J = 0.30 \sim J = 0.45 \))
Figure 14. Comparison of Axiom I (Left) and Axiom II (Right) for \(J = 0.30\) and \(V = 3.0\) m/s

Figure 14 shows a comparison of the Mark I and the Mark II Axiom propellers from the different tests. From this figure it is clear that the Mark II is more heavily loaded at the same test condition, whereas the Mark I with its smaller pitch ratio is still transitioning into unsteady cavitation range. The Mark II however, will typically operate cavitation free at \(J = 0.55\) the tentative design point. Finally Figure 15 shows the cavitation patterns for the multi-quadrant tests. In this figure it is easy to see the conventional cavitation pattern associated with first quadrant testing at \(\beta = 5^\circ\) however as the quadrant changes to the second quadrant by \(\beta = 175^\circ\), where the flow is forward and the propeller reversing the cavitation switched to the back of the propeller (suction side), generating tremendous levels of noise and vibration. This condition would represent a transitory phase in stopping a vessel and not a steady state condition.

6. CONCLUSIONS

This paper presented the cavitation tunnel tests for a 300mm diameter, 3 bladed bi-directional thrust propeller. These tests were conducted to verify the propeller’s efficiency the multi-quadrant performance and cavitation characteristics. Based on the tests it was found that:

- Maximum efficiency of the Mark II Axiom propeller was measured at 53%; this was obtained during the first quadrant / open water test.
- Bearing in mind the differences in the P/D, BAR and outline shapes, the Mark II version of the propeller can provide 63% more efficiency over the Mark I version under similar conditions.
- Useful, comparative multi-quadrant data for the two Axiom propellers are presented. The data reflected the symmetric feature of the propellers. The ahead and astern (thrust and torque) performance of this bi-directional thrust propeller was
shown to have skew symmetry requiring only 2 quadrants to be tested.

- In the first quadrant, the main cavitation patterns were a strong steady tip vortex and leading edge sheet cavitation at the suction (back) side of the blades. The extent and interaction of these cavities increased with reduced $J$ value. The mid chord sheet cavitation was potentially erosive however the design point for this propeller is well away from the cavitation condition.

- The Mark II Axiom propeller with the new tapered outline shape would benefit from the inclusion of a duct to suppress cavitation and increase performance further. However the Axiom Mark II design, for the condition shown, does not operate in a cavitation zone.

REFERENCES

Atlar M. (2011) Recent upgrading of marine testing facilities at Newcastle University. AMT’11, the second intl. conference on advanced model measurement technology for the EU maritime industry, Newcastle University, UK, 4–6 April.


Sampson, R., Atlar, M., Politis, G. (2012) AXIOM Mark II Propeller: Multi - quadrant open water tests, School of Marine Science and Technology, Newcastle University, Technical Report, MT/CT-2012-001